Studying Neutrino Oscillations with the NOvA Detectors
IF Fellowship Activity Report

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Supported by a Fermilab Intensity Frontier Fellowship, my research group and I relocated to Fermilab in Batavia, Illinois from October 2013-July 2014. The fellowship provided funds for travel, housing while at Fermilab, and also covered 20% of my salary for six months. While at Fermilab, my group and I worked on constructing and commissioning the NOvA detectors. Additionally, I continued my role as a MINOS collaborator, and constructed a prototype detector for a new detector R&D effort, CHIPS R&D.

The NOvA experiment will study neutrinos from the NuMI beam in two massive detectors. One neutrino detector is placed close to the muon neutrino source on site at Fermilab. In this detector, we establish the properties of the beam as soon as it is created. It serves as the control for the experiment. The other detector is placed over 500 miles away, in Ash River, Minnesota. In that detector, we look for any differences in the beam after the neutrinos have traveled hundreds of kilometers, through the crust of the earth. Differences in the neutrino beam observed between the near and far detectors are evidence of neutrino oscillations. In particular, NOvA is interested in measuring an excess of electron type neutrinos in the far detector. The electron neutrino appearance probability will be measured for both neutrinos and antineutrinos. Differences between the two may reveal the order of the masses of the neutrinos or perhaps a hint of charge-parity violation in the neutrino sector. A new source of charge-parity violation is required to explain the matter-antimatter asymmetry we observe in our universe. After years of construction, the experiment has begun to collect data. Preparations are currently underway to produce an initial result from our first data set.

When we relocated to Fermilab, the far detector was under construction. Near detector construction had not yet started. A delay in the project meant that I would not be performing the analysis of the data while on sabbatical as proposed. Instead, I, and more importantly my postdoc and graduate students, got the valuable opportunity to contribute to the construction and commissioning of new particle detectors. Our detectors are made up of long cells of rectangular PVC pipe. These cells are filled with liquid scintillator, an oil based material that makes light when charged particles traverse it. Fiber optic cables in the scintillator collect the light and route it outside the detector to Avalanche Photodiodes (APDs), silicon devices that output an electrical current in proportion to the amount of light incident on the device. The far detector is made up of over 300,000 of these cells, and weighs in at 14,000 tons. Measuring 15 meters wide, 15 meters tall, and 60 meters tall, it is rumored to be the largest plastic structure built by man[1]. The near detector is a smaller version of the far, weighing just a few tens of tons.

I and each of the researchers under my supervision played key roles in detector installation and commissioning. The Near Detector construction was accomplished primarily by volunteer effort from collaborators, and my group contributed significantly to that effort. My graduate student Ji Liu moved to Fermilab in August, 2013 and stayed until January, 2014. She was responsible for checking the cells of the near detector for possible leaks. She had to run her tests before the cells were glued into blocks, and then again once those blocks were transported from the assembly building to the underground cavern that would house the near detector. Once all the cells were installed underground, she also helped with the installation of the cables and readout electronics and with the initial scintillator filling. Graduate student Marco Colo replaced Ji at Fermilab in January. Marco was responsible for testing the APDs as they arrived at the lab, and then installed the devices on the detector. He stayed at Fermilab until the near detector installation was complete in August, 2014.

I personally contributed to the commissioning of the far detector. The checkout of the new hardware that was installed was carried out from Fermilab. I joined the small team tasked with debugging and diagnosing the different failure modes. With over 300,000 channels, even a small failure rate meant a lot of equipment had to be replaced. As with any complicated device, it wasn't immediately clear which pieces had failed and needed to be replaced. We developed a series of tests and checks to isolate the faulty piece of equipment, and provided a weekly list of what needed to be repaired or replaced. I also developed the routine to set the high voltage input to each APD to achieve a uniform gain throughout the detector. I was also able to relieve a Fermilab postdoc from some of his duties as the system on-call expert, so that he could concentrate on analysis work.

In Fall, 2013, I hired a new postdoc, Alex Radovic, to work on NOvA. He is still based at Fermilab. Alex is a detector timing system expert, meaning he is responsible for making sure all the different parts of detector hardware are properly synchronized. He also works on calibrating the detector, making sure that each cell of the detector responds the same when a particle crosses the cell. This is a crucial step in understanding the data we collect. Beyond taking care of low-level detector maintenance issues, Alex has assumed a lead role in the oscillation analysis. He is head of the beam systematics working group, the group that studies the systematic errors associated with the neutrino flux and their implications for the oscillation analysis.

As of Fall 2014 both detectors are complete and recording neutrino beam data. Initial results on cosmic ray rejection were presented at Neutrino 2014 in Boston. Now our attention turns to the analysis of the neutrino data we are collecting. I lead the working group

[1]The application to the Guinness Book of World Records is still pending.

responsible for developing the primary NOvA analysis, the identification of an excess of electron type neutrinos in the far detector, relative to what we measure in the near detector. While we had developed many of the tools and techniques of the analysis using simulation, the exciting work starts once we start exercising those tools on real data. The first step in the process is understanding the data collected in the near detector. This includes running simulations of the detector and comparing the real data to the output of the simulation. Ji is a pioneer in this activity and has uncovered a number of discrepancies between data and simulation. We are slowly developing a more robust detector model, and gaining confidence that we understand how the detector works, at least well enough to use the data in an initial analysis. That first analysis is expected in Spring 2015.

In addition to my NOvA responsibilities, I was also named co-convener of the MINOS+ standard oscillations working group. This working group is responsible for analyzing the MINOS+ data in the context of standard three flavor oscillations. During my time at Fermilab, we extended our analysis to include another two years of atmospheric data, and we took a preliminary look at the first set of Far Detector data collected in the new medium energy beam. The Far Detector spectrum is consistent with the oscillated prediction made using parameters measured in the low energy beam. Being on site with a large contingent of the students and postdocs working on this analysis helped to turn this analysis around quickly. This first result from MINOS+ was presented at Neutrino 2014. I continue to lead this working group to produce a measurement of the oscillation parameters using the entire first year of data collected in MINOS+.

Finally, while at Fermilab, I helped make preparations for building a prototype submergible Water Cherenkov neutrino detector, a project called CHIPS R&D. This new detector concept is being pursued to develop lower cost neutrino detectors, with the aim of bringing Megaton detectors within budgetary reach. These large detectors would be submerged in natural or man made bodies of water, in the path of existing or planned neutrino beams. The water serves both as structural support for the large detector, eliminating the need for large initial investment in expensive infrastructure, and as an overburden, eliminating the need for underground caverns. The prototype detector uses IceCube photomultiplier tubes and DAQ. Proximity to Madison was beneficial in the initial stages of the project as it allowed for closer collaboration with the experts at Wisconsin IceCube Particle Astrophysics Center. Our initial prototype was constructed and deployed during Summer 2014. It is now taking cosmic ray data in the Wentworth Pit of Northern Minnesota, a flooded mine pit in the NuMI beam line. Lessons learned from 2014 deployment and operations will be incorporated into a conceptual design of a 10 kton detector.

In summary, the Intensity Frontier fellowship made it possible for me and my group to relocate to Fermilab during my year of research leave. My students and postdoc gained experience building and commissioning detectors. The foundations for the on-going NOvA oscillation analyses were laid. Close collaboration among the MINOS+ standard oscillation group allowed for quick turnaround of MINOS+ results, and the new CHIPS R&D detector project succeeded in deploying its first prototype detector.